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DMIC Report S-25

June 1, 1968

CURRENT PROBLEMS IN PREVENTION OF FATIGUE

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Battelle Memorial Institute

Columbus, Ohio 43201

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2. To supplement established Service activities in providing technical advisory services to producers, melters, and fabricators of the above materials, and to designers and fabricators of military equipment containing these materials.

3. To assist the Government agencies and their contractors in developing technical data required for preparation of specifications for the above materials.

4. On assignment, to conduct surveys, or laboratory research investigations, mainly of a short-range nature, as required, to ascertain causes of troubles encountered by fabricators, or to fill minor gaps in established research programs.

Contract No. F 33615-68-C-1325

Roger J. Runck

Roger J. Runck
Director

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DMIC Report S-25
June 1, 1968

CURRENT PROBLEMS IN PREVENTION OF FATIGUE

by

H. J. Grover and A. A. Mittenbergs

to

OFFICE OF DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
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Columbus, Ohio 43201

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A SURVEY REPORT OF CURRENT PROBLEMS IN PREVENTION OF FATIGUE

H. J. Grover and A. A. Mittenbergs*

INTRODUCTION

The literature on fatigue of metals is voluminous and is growing rapidly. It is estimated that more than 8000 articles exist, that these are increasing by at least 800 per year, and that the increase is growing more than 10 percent per year. This does not include an immense number of articles (such as those on fracture mechanics or those on nondestructive inspection) which are pertinent but not directly listed in regard to fatigue.

A number of books and summary articles deal with fatigue [see, for example, References (1) through (12)]. With few exceptions [and these generally are older books such as Reference (1)], each emphasizes a particular aspect such as basic mechanisms(8), low-cycle fatigue(5), or fatigue of aircraft structures(2,3,6,9). Moreover, there appears to be no summary account that covers completely such practical considerations as field inspection for warning of fatigue damage.

Accordingly, the Defense Metals Information Center ~~was requested to~~ conduct a brief survey of the present state of knowledge about fatigue with wide coverage as to applications and with particular emphasis on means of early detection of fatigue damage.

The survey has excluded consideration of reports of proprietary interest and of reports with security classification. However, it has included information from various branches of the U.S. Army, the U.S. Navy, the U.S. Air Force, and the National Aeronautics and Space Administration. In addition, considerable background information has been available in the files of the Defense Metals Information Center and in the records and experience of other groups at Battelle's Columbus Laboratories. This survey is based on information selected from several thousand reports that have been available.

The results of such considerations as have been possible are described in the following pages with the objectives of:

(1) Delineating the current state of knowledge;

(2) Indicating some of the current research toward increasing this knowledge; and

(3) Pointing out areas where further work seems desirable.

THE BASIC MECHANISMS OF FATIGUE

Fatigue has been defined as "the process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations". A great deal of effort has been expended toward obtaining some insight into why excessive structural damage and cracking may be caused by fluctuating stresses in contrast to less severe disruption under a steady stress of the same maximum value. While present understanding is incomplete, considerable progress has been made.

Major advances were made by and summarized in the work of Gough(13). He showed that fatigue cracking in ductile metals is a consequence of local slip. Some years ago, Orowan(14) emphasized the importance of redistribution, subsequent to local slip, of local stresses and strains in successive fluctuations of loading.

More recently, improved techniques of observation (such as use of the electron microscope and of etch pit techniques for indicating dislocations in certain materials) have permitted study of details of the local slip under cyclic stressing. There now exists considerable evidence that fatigue cracks usually start at a free surface in notches created by the local slip developed under repeated stresses. These notches may be extrusions or intrusions or other discontinuities depending on the material and on the local stress field. The manner in which the local slip develops and produces notches (and eventually microcracks) is the subject of much current study. Grosskreutz(8) has summarized the state of knowledge up to a few years ago and, with support from the Air Force, is pursuing further studies and attempting to keep abreast of current research in other laboratories.

Dolan(8) has pointed out that increased understanding of the nature of fatigue may be sought at various levels of consideration as suggested in Figure 1. As one proceeds from Level (a) to Level (d), each step introduces additional factors that influence fatigue behavior. Considerations at the level of the physics of solids usually refer to single-crystal specimens and involve such departures from extreme simplicity as the presence of dislocations in the crystal. At the next level, designated for convenience as the level of metallurgy, added parameters are crystals with varied orientation with respect to the nominal stress field, intercrystalline boundaries, possible precipitates of other phases, and, in practical materials, inclusions and voids. The ordinary laboratory test coupon involves also items of design (such as necessary fillets) and of fabrication (working, machining, and surfacing). Components include additional parameters of design and complexities of stress analysis as in fasteners. Finally, a complex structural assembly may have assembly stresses and load distributions not accountable in engineering stress analysis; moreover, in many situations, service loadings are not known with exactness.

It is somewhat a matter of semantics as to what level constitutes basic mechanisms. In this survey we will consider this to include both Level (a) and Level (b) in Figure 1. On this basis it is clear that even if basic mechanisms were thoroughly understood, it would not necessarily be possible

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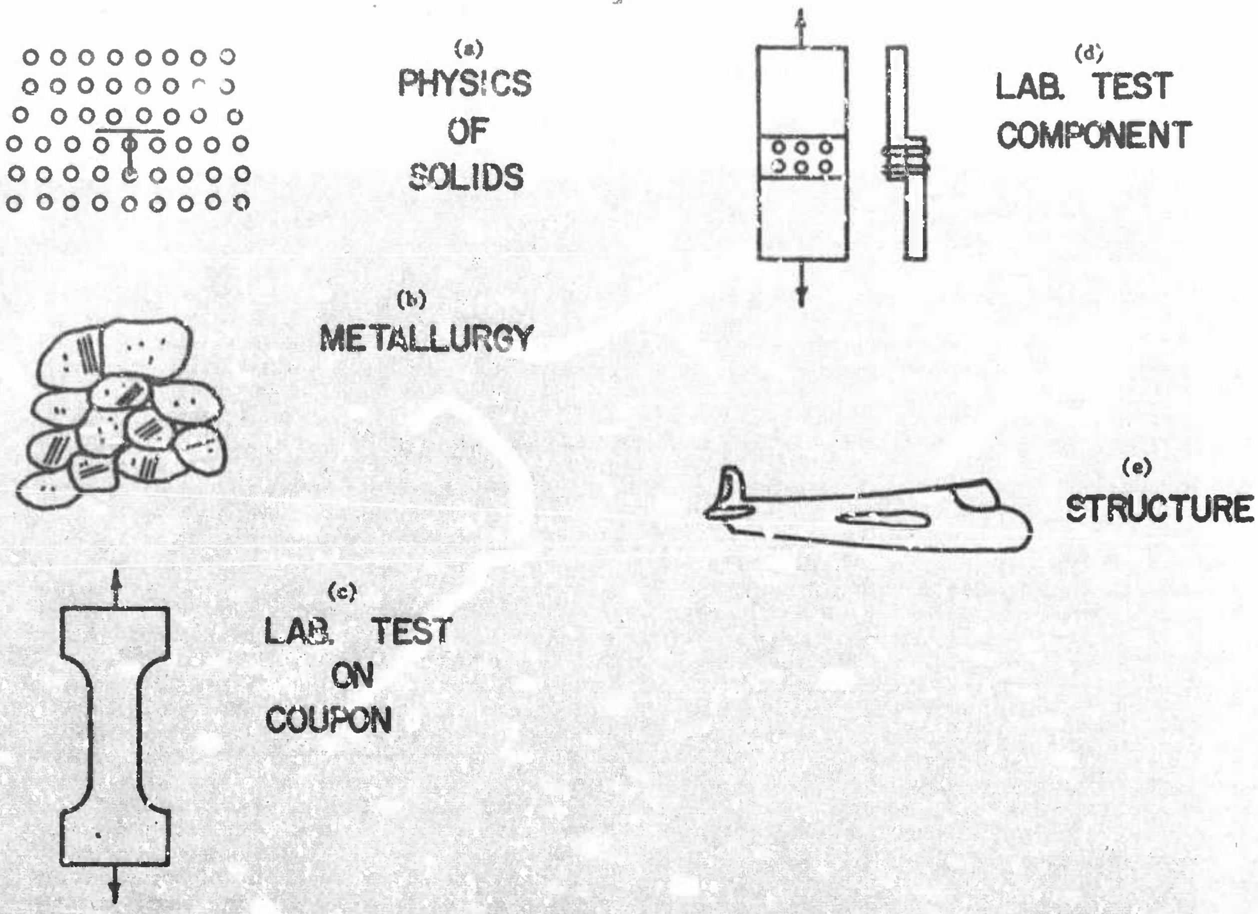

FIGURE 1. VARIOUS LEVELS OF CONSIDERATION

to construct a complex assembly with complete reliability. Additional factors in the assembly will be too numerous (and frequently too imperfectly known). Hence, structural testing and allowance for statistical variation of various factors will remain necessary even when basic mechanisms of fatigue become well understood.

Study of basic mechanisms is important because this may (1) provide clues to improve materials and (2) develop sound bases for empirical testing and design formulations. Such research is currently being sponsored by many Government agencies and also pursued independently by some industrial laboratories and laboratories of universities and of research institutes. Many of the developments that seem pertinent to aircraft are summarized regularly at meetings of the International Committee on Aeronautical Fatigue (ICAF) by the U.S. representative.(15) Other readily available sources of information about current progress are the reports of ASTM Committee E-9 and summaries of research by the Air Force, the Army, and the Navy (these may be available only to qualified requestors).

In summary of this brief account of the status of information on the basic nature of the fatigue of metals, it appears that:

(1) The process is directly concerned with localized slip. While many observations of details have been made with modern techniques, the critical mechanisms have not been fully delineated.

(2) Considerable work is going on, but a complete understanding does not seem imminent.

(3) Many complicating factors have been identified, including some significant ones in processing, in design and fabrication, and in assembly.

Because of Item (2) and Item (3), it is now necessary to seek much practical information on an empirical basis. Because of Item (3), this requirement is likely to remain for the foreseeable future.

EMPIRICAL INFORMATION CONCERNING FATIGUE

Empirical information may be obtained by tests of material coupons, components, or complete structures. Tests may be run on carefully prepared metal coupons with the objective of obtaining data on the potentialities of a particular material in one or more specific conditions of metallurgical structure. Tests on components may bring out additional features of the response of the materials to such factors as: design discontinuities, fabrication processes, welding, or other joining procedures. Tests of large assemblies (up to and including full-scale structures such as a complete aircraft) provide information about further factors such as assembly stresses, possible unexpected distribution of stresses and strains from external loads, and effects of complex load-time patterns simulating those anticipated in service. For each of the three classes of tests, there are many possible variations so that a complete summary is impossible in a limited discussion.

The three, in the order listed, present decreasing generality of application: information from fatigue tests on a material may be applicable to many uses of that material, while information from fatigue tests on a structure may be mainly applicable only to closely similar structures. Accordingly, the following discussion emphasizes the empirical information from fatigue tests on materials and is intended mainly to outline the kind of information available (and possible gaps in such information).

Empirical information on the fatigue properties of materials has been summarized [see, for example, References (1) through (12) and (15) through (20)]. Nevertheless, there are two reasons for a brief account here: (1) there are, as will be noted, some areas in which it seems more difficult to get data on the fatigue properties of materials and (2) some background in regard to empirical observations is important to assessment of the potentialities and limitations of means of inspection for incipient fatigue damage.

"Conventional" Fatigue Tests

The most extensive tests of the fatigue properties of materials have been run at varied ranges of stress amplitude, and results have been reported in the form of S-N curves such as illustrated in Figure 2. There are several conventions:

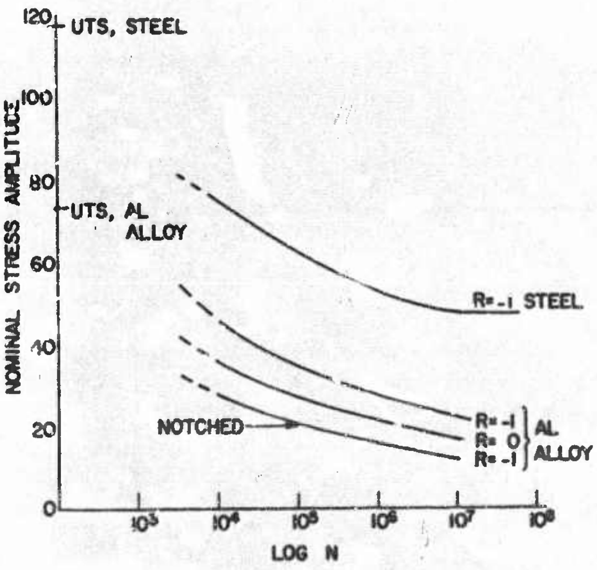

FIGURE 2. "CONVENTIONAL" S-N CURVES

(Tests run at constant stress-amplitude and to failure by rupture)

(1) For each specimen, the stress amplitude is held constant during the test, and so is some selected value of mean stress.

(2) The mean-stress condition is designated by a value of R (ratio of minimum stress to maximum stress) or of A (ratio of stress amplitude to mean stress).

(3) The stress values are "nominal"; that is, without adjustment for stress concentration factors.

(4) Failure is usually complete fracture of the small test specimen.

(5) "Curves" are usually drawn "by eye" through data points; information is only occasionally enough for formal statistical evaluation [see, however, Reference (16)].

When tests have been run at several values of R (or of A) constant-lifetime diagrams (often called Goodman diagrams) like that in Figure 3 may be derived. Such a diagram provides a compact representation of considerable data. Many such diagrams are given in MIL-HDBK-5A(17) for materials of interest in aircraft and aerospace vehicles; these have been derived on the basis of careful consideration of rather extensive data. Table 1 lists alloys for which such data are now available.

There are several sources of data on other materials, although these data are generally less complete and less thoroughly assessed. MIL-HDBK-5A has some tabulated values for materials for which there is too little information available to plot diagrams such as Figure 3. The Aerospace Structural Metals Handbook(18) (of somewhat limited availability) has a fair amount of "typical" fatigue-test data. The Highway Structures Design Handbook(19) has some fatigue-test data on structural steels (including Cor-Ten and T-1). A report written several years ago(16) contains a considerable collection of fatigue-test data on steels. Belfour Stulen, Inc., operates a Mechanical Properties Data Center under contract to the U.S. Air Force; properties (including fatigue test data) are stored on IBM cards or on magnetic tape; for a service charge, a requester can obtain data, including correlative information (composition, heat treatment, etc) on fatigue behavior of materials for which the Center has information.

Some general comments on the available "conventional" fatigue-test data are:

(1) Many data are available. However, the number of possible combinations (composition, heat treatment, test-specimen design and preparation, and testing conditions) is so large that data exactly appropriate to a specific need may not be found. Interpolations may be useful; extrapolations may be unwarranted.

(2) Materials of wide use in the aircraft industry have been especially thoroughly studied and test results for these materials have been evaluated and collected in MIL-HDBK-5A. Data on some other materials (including many structural steels) are less well organized and available.

For reasons noted in subsequent sections, there are limitations to the practical applicability of the "conventional" fatigue-test data.

Low-Cycle Fatigue Tests

When nominal stresses are high (and the lifetimes short), the constant stress amplitude test has limitations. Strains have large plastic components and are not directly proportional to stresses. Figure 4 shows a suggestion by Manson(5) that a logarithmic plot of the amplitude of plastic

TABLE 1. LIST OF MATERIALS FOR WHICH THERE ARE "GOODMAN" DIAGRAMS IN MIL-HDBK-5A

Material			Test Condition		
Class	Specific Designation	Ultimate Tensile Strength[a], ksi	Unnotched	Notched	Temperature, F
Steel	SAE 4340	125.0	X	K_t = 3.3	RT, 600, 800, 1000
		158.0	X	K_t = 3.3	RT
		206.0	X	K_t = 3.3	RT
		260.0	X	K_t = 3.3	RT
PH 15-7 Mo	TH 1050	201.0	X	K_t = 4.0	RT, 500
17-4 PH	H 900	201.5	X	K_t = 3.0	RT
Aluminum alloy	2014-T6	70.0	X	K_t = 3.4	RT
	2024-T4	68.0	X	K_t = 3.4	RT
	6061-T6	45.0	X	---	RT
	7075-T6	82.0	X	K_t = 3.4	RT
	2024-T3	73.0	X	K_t = 1.5, 2.0, 4.0, 5.0	RT
	7075-T6	82.5	X	K_t = 1.5, 2.0, 4.0, 5.0	RT
A-286		147.0	X	---	1350
N-155		(80 at 1200 F)	X	K_t = 1.73, 3.2, 5.0	1200
		(80 at 1200 F)	X	K_t = 5.1	1500
Udimet 500		---	X	K_t = 3.4	1200, 1650
Titanium alloy	8Al-1Mo-1V	147.0	X	K_t = 2.47	RT, 400, 650[b]
	4Al-3Mo-1V (STA)	196.0	X	K_t = 2.82	RT, 600, 800
	6Al-4V	172.0	X	K_t = 2.82	RT, 600, 800
	13V-11Cr-3Al	138.5	X	K_t = 3.0	RT, 600, 800
	13V-11Cr-3Al	174.5	X	"	RT, 600, 800

(a) UTS at RT, except for N-155.

(b) Exposed at 25 ksi, 500 hours at 400 F, and 5000 hours at 650 F.

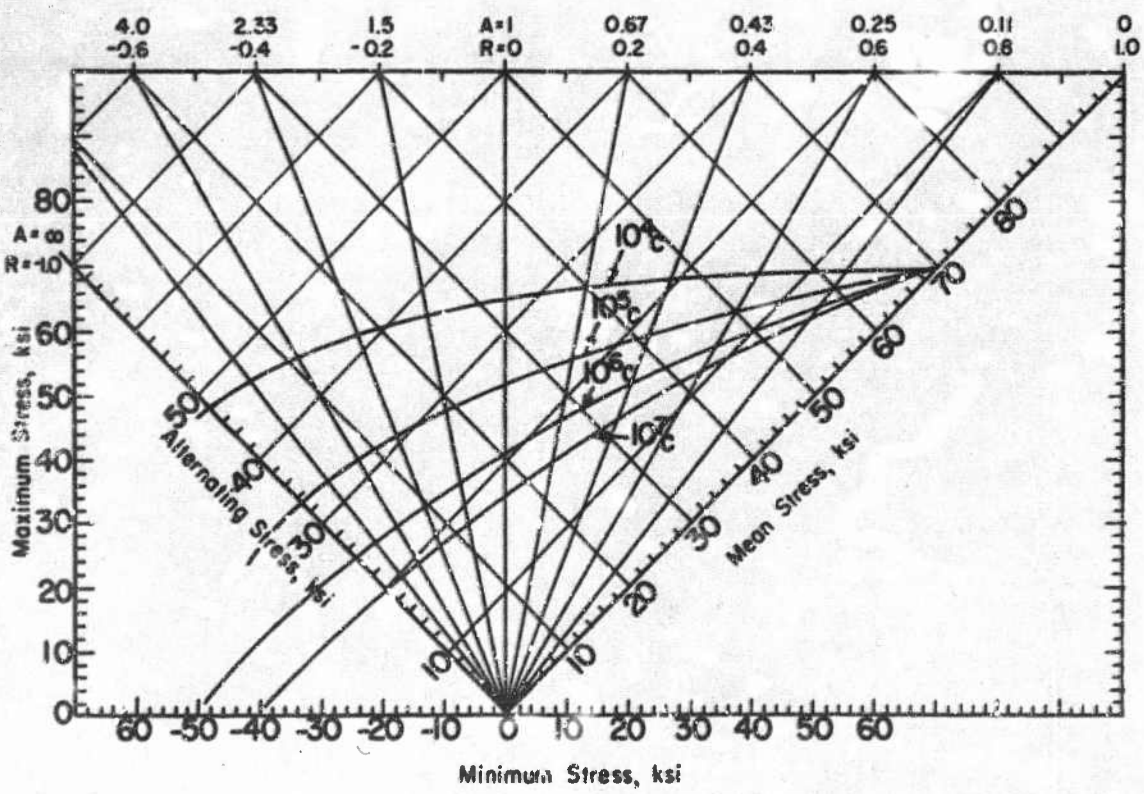

FIGURE 3. A CONSTANT-LIFETIME (GOODMAN) DIAGRAM

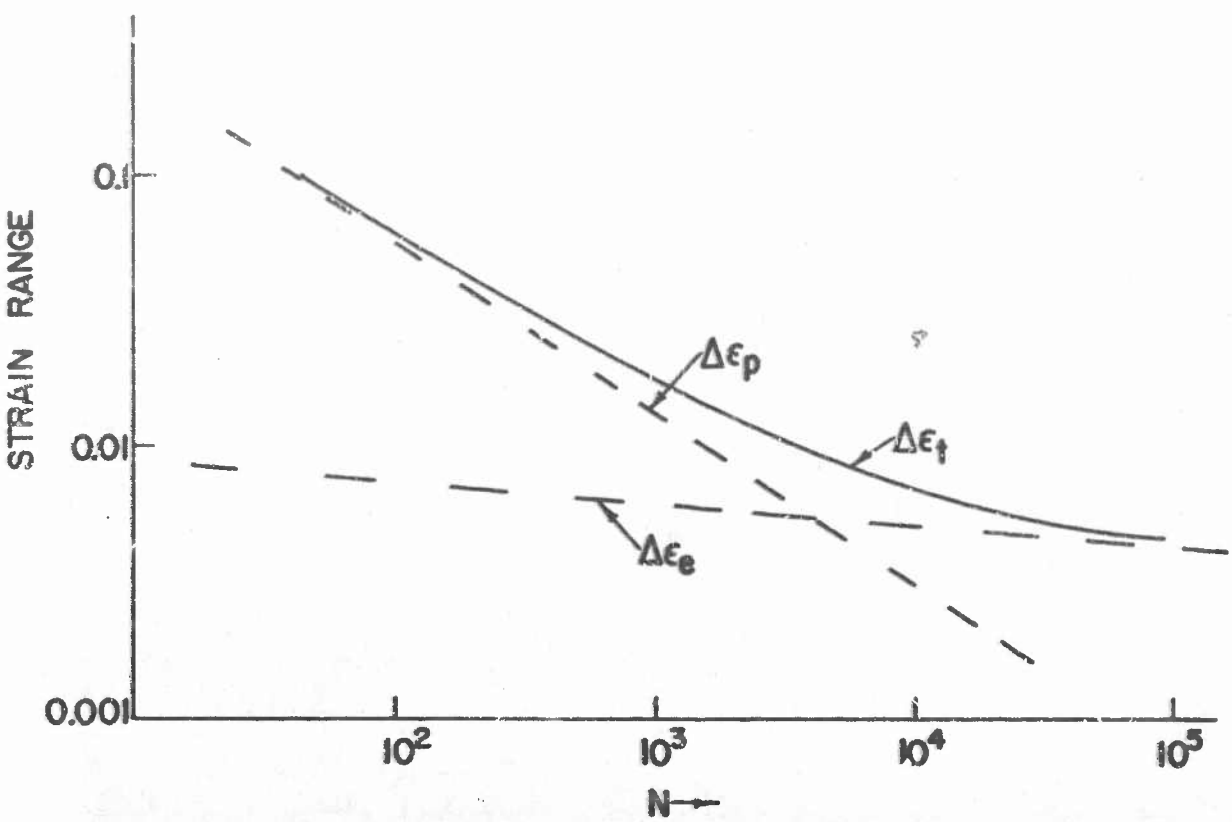

FIGURE 4. METHODS OF REPRESENTING FATIGUE TEST RESULTS OVER A LARGE RANGE OF LIFETIMES

(Note: curves approximately fitted to data in annealed 4130 steel)

strain, $\Delta\epsilon_p$, or of the amplitude of elastic strain, $\Delta\epsilon_e$ against lifetime may give an approximately straight line but a logarithmic plot of the total strain amplitude, $\Delta\epsilon_t$, against lifetime may be curved. Manson's book provides a good account of information on low-cycle fatigue behavior and a considerable collection of data; he has additional data in later papers [see, for example, Reference (20)]. Additional information on low-cycle fatigue behavior may be found in numerous recent reports.[(21-26)] Work in this field is currently being sponsored by the U.S. Navy, the U.S. Air Force, and NASA--generally on materials and under conditions of particular interest to the agency sponsoring each task. The Metals Properties Council of the Engineering Foundation is sponsoring work including a literature search on low-cycle fatigue in power generation and chemical and petroleum equipment.

Coffin, in a recent article[(27)], writes "a degree of information now exists for the low-temperature (below the creep range), low-cycle fatigue problem, although there are a number of unresolved questions ... The material behavior becomes very much more complicated at elevated temperatures because of the occurrence of creep and other diffusion processes".

Fatigue-Crack Propagation

As illustrated in Figure 5, the progress of fatigue may be considered in three stages:

(1) In some number, N_1, of cycles, a small crack develops. There may be two substages: initiation of a microcrack and early growth of this to a somewhat larger crack.

(2) Propagation of a crack, for N_2 cycles, occurs in a manner which may follow a rather regular "law".

(3) Final rupture, perhaps in a quarter cycle, occurs after the crack has reached a length critical for the material, the applied load, and the test piece or structural part. Evaluation of the critical crack length before rupture can be of major importance in estimating the fatigue life of a structural component.

In the past 5 years, a great deal of attention has been devoted to stage (2), crack propagation. A recent review of theories[(28)] not only summarizes many of the approaches that have been suggested, but also contains a significant amount of data on aluminum alloys and a bibliography of some 133 references.

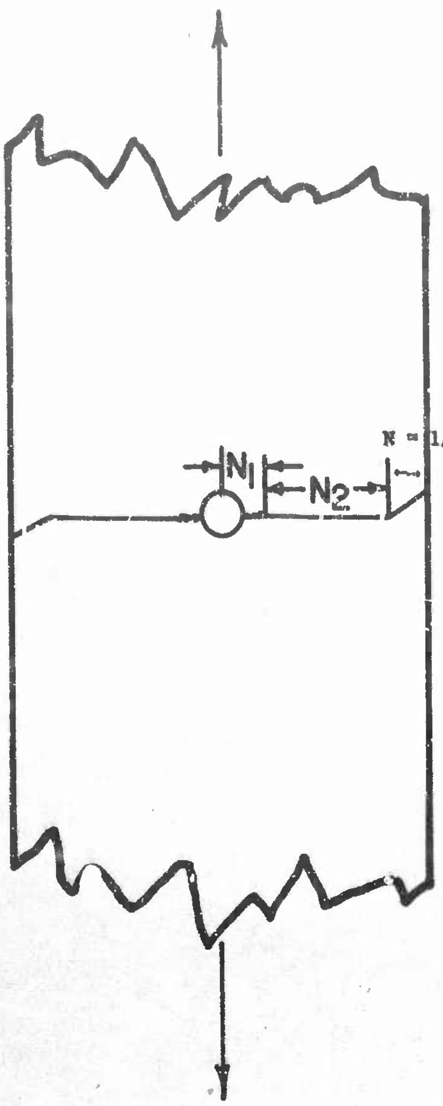

FIGURE 5. THREE STAGES OF FATIGUE-CRACK PROPAGATION

Many investigators have tried to develop relations of fatigue-crack growth rates and the linear fracture mechanics stress intensity (see paper by P. C. Paris(8)). At present, it seems uncertain to what extent (particularly in the range of high stresses and gross plasticity) this approach will be fruitful.

Some additional data on fatigue-crack propagation are given in References (29) through (36). These indicate not only current interest in fatigue-crack propagation, but also concern for the effect of such parameters as temperature and environment on rates of crack growth.

A practical concern is that a material with greater resistance to fatigue-crack initiation than another material may not necessarily have slower crack growth nor endure a larger critical crack length before catastrophic rupture. Which property is more important for a specific application depends on details of that application. Realization of the possible importance of the propagation stage also affects inspection considerations--as discussed later.

Cumulative Damage in Fatigue

Many critical parts of structures undergo loading conditions more complex than a repeated constant amplitude of stress (or of strain). A complex spectrum can be analyzed in terms of n_i cycles at each nominal stress amplitude S_i. The most widely used criterion of fatigue under such complex loading is the Miner-Palmgren relation

$$\sum_i n_i/N_i = 1,$$

where N_i is the number of cycles to failure under a constant stress amplitude, S_i. Now it has been shown that this criterion is wrong in special cases, and numerous alternative "theories" of cumulative damage have been suggested.(3) Some of the considerations of redistribution of local stresses and strains have been clarified but there is yet no approach that seems satisfactory in all cases.

The situation has important implications in engineering practice. One recourse has been to test components and/or full-scale structures under a spectrum of loading considered representative of expected service; this entails questions of proper representation of service loadings and possible effects of statistical departures of individual structures from the representative loading in the test. Cumulative damage under a load spectrum also requires consideration of inspection and maintenance.

Environmental Factors

As conditions of use of materials become more severe and as more efficient behavior of materials is pursued, effects of environments become increasingly important. This discussion considers three environmental factors: temperature, frequency, and "corrosive" surroundings.

Various means of increasing engine performance and the development of supersonic aircraft are promoting increasing interest in elevated-temperature performance in fatigue. This involves consideration of such items as: thermal stresses and stress cycles, degradation of material strength under elevated-temperature exposure, and the interaction of creep and fatigue. These considerations are currently being pursued especially by and under sponsorship of the U.S. Air Force and NASA. On the other hand, there is (in connection with space vehicles and other applications) increasing interest in fatigue at cryogenic temperatures. Reference (37) indicates some of the current considerations in this area and includes a short bibliography.

Frequency is one of the factors affecting acoustic fatigue, which is also affected by creep at elevated temperatures and corrosion fatigue interactions. In this area, there are particular difficulties in relating the acoustic field to fatigue behavior of materials such as indicated in conventional S-N curves. A large part of the difficulties involves translation from acoustic descriptions of the field to local stresses and strains in the material; such translation is extremely dependent on geometry. Another concern is damping properties of material. Some of these considerations are discussed in Reference (38).

The interaction of the environment with the fatigue behavior of a metallic structure is of increasing importance in many applications. Perhaps the most concern about environmental factors in fatigue has been expressed by the U.S. Navy. Although other "corrodents" are important in particular applications, the effect of saline water is an outstanding problem. Accordingly, many investigations of this are being pursued both "in-house" and through contracts by various branches of the Navy. At present, there is much evidence that an aqueous environment (particularly one with metallic salts) can be extremely detrimental to the resistance of a material both to fatigue-crack initiation and to fatigue-crack propagation. There is not yet a complete understanding of the mechanisms involved and the number of parameters is very great so that empirical results are hard to generalize. Another concern is that of fretting and resulting fatigue-crack initiation; the effect of fretting is generally very dependent on environment. Some account of factors in corrosion and fretting is given in Reference (3).

SOME CURRENT PROBLEM AREAS

The large number of parameters affecting fatigue behavior and the great variety of significant details in application make it difficult to generalize about problem areas. The following notes are intended to illustrate some current concerns. The items are based on several publicly available reports, a few reports made available for this survey, and discussions with individuals in various Government agencies.

Quality Control

It is true today, and may be expected to be true in the foreseeable future, that many fatigue failures in service may be attributed to imperfect control of material (including impurities, heat treatment, and strain hardening) and of fabrication (including forming, machining, and joining). In such instances, it is not lack of technological background that is contributory so much as lack of training of inspectors to appreciate details that can be important in fatigue and lack of communication among all concerned with design and production and maintenance, and lack of time and effort in the exigencies of getting some vehicle into or back into service.

One effort toward helping improve shop practice and inspection procedures is illustrated by the U.S. Navy publication of pamphlets such as "Tips on Fatigue"(39) that point out some of the many defects which can decrease the resistance of a part to fatigue. Another help is the development of improved techniques of inspection toward elimination of possible uncertainties in human judgment.

Materials and Processing

The aluminum alloys so extensively used in aircraft have been relatively thoroughly explored in regard to fatigue behavior. These have been studied with respect to many conditions of importance in application: under axial loading at many values of mean stress, for many severities of notching, at low cycles as well as for long-lifetime fatigue, with regard to crack propagation as well as total time to rupture, and under several conditions of temperature and of environment. Although steels were studied in fatigue before the aluminum alloys, it is more difficult to find systematically tabulated extensive data, except perhaps on SAE 4130 and SAE 4340 steels. A number of "new" steels (Cor-Ten, Man-Ten, T-1, HY-80, maraging, etc.) have been tested in fatigue under somewhat limited conditions so that assembling a relatively complete picture for any one is difficult. In general, the tests that have been run on these materials have related to particular application problems.

There is current interest in titanium alloys--and these are beginning to have a considerable background of empirical fatigue-test data.(40-43) Stainless steels and special alloys for elevated-temperature applications are also being studied rather extensively.

The number of parameters for consideration in a material such as a steel of particular composition makes assessment of the complete picture of fatigue behavior time consuming. In addition to the variables in heat treatment, many processing factors require consideration.

Industrial metals and alloys are not entirely uniform in composition or density. Among variations in the ingot stage are porosity, segregation of chemical elements, and impurities. The latter may be present in solution or as mechanically held particles called inclusions. Fatigue behavior is sensitive to most inhomogeneities and particular attention has been given to the importance of inclusions. Undoubtedly, the variations in inhomogeneities resulting from melting practices contribute much to the observed "scatter" of fatigue strength properties of specimens of any alloy. Since there is no positive way to eliminate inhomogeneities, it is necessary to use the cleanest material possible and then allow for scatter in the fatigue strength.

The mechanical working of an ingot, as in forming, rolling, or extrusion, tends to break up inclusions and to give a preferential orientation to grains and to leave residual stresses. These tendencies influence the fatigue strength of the wrought material. Thus, the fatigue behavior of a particular material must be assessed for the particular condition, cast or wrought, in which it is to be used.

Heat treatment and hardening are other processing variables. Carbon and low-alloy steels are transformation-hardening alloys. That is, they are strengthened by a fast transformation from austenite to mixtures of ferrite and carbide. There are a number of procedures which may be followed in heat treatment to produce such a transformation. These include: rapid quenching and tempering, martempering, austempering, maraging, marstraining, and ausforming. Not all of these are suitable for all steels in all section sizes, but those suitable for a particular steel need consideration as parameters influencing the fatigue behavior of the final product. In many nonferrous metals (aluminum alloys and titanium alloys are examples) hardening is produced by precipitation of small particles that inhibit deformation processes. This may be obtained by rapid cooling from a high temperature (a solution heat treatment) followed by aging at room temperature or at an elevated temperature. For some alloys, stretching in the solution-treated condition before aging modifies the properties. Some high-chromium steels with the addition of nickel retain the

austenitic structure on quenching, but the crystalline state can be realigned by plastic deformation to result in a harder material--this is called strain hardening. The effect of strain hardening also influences the fatigue properties of the product.

All of the methods of hardening produce increases in static strength properties but generally less than a proportional increase in fatigue strength. Moreover, in most cases, the notched fatigue strength does not increase as rapidly with increasing tensile strength as does the unnotched fatigue strength. Thus, complete assessment of a material requires consideration of the parameters of forming and of heat treatment or hardening as well as those of composition and degree of purity.

Since fatigue cracks almost always start at a free surface, the condition of the surface is an important factor in the fatigue behavior. There are metallurgical surfacing processes (such as case hardening of steels), chemical surface processes (such as pickling, etching, surface deposition), and mechanical surface treatments (such as peening and rolling). Surface processing is an important parameter in the fatigue behavior of a material.

Because assessment of the fatigue characteristics of a material requires consideration of so many parameters, such assessment is seldom complete. Preliminary estimation can be made by taking such fatigue data as are available for particular conditions and modifying these from general knowledge of the effect of different parameters on alloys of the same class to whatever condition may be of interest for a particular application. Such estimates are necessarily speculative and warrant checking by direct experimental tests whenever fatigue strength of the material is an important consideration.

Long-Lifetime Fatigue

A majority of fatigue failures in aircraft (both helicopters and fixed wing) have been "long-lifetime" ones--say, 100,000 cycles or more. This is an area in which consideration may be in terms of nominal stress (rather than nominal strain) values.

Some idea of areas of interest for aircraft may be obtained from the reviews presented at meetings of the International Committee on Aeronautical Fatigue.[15] Areas of current research include: basic mechanisms, effects of metallurgical parameters, new materials and extension of use of existing materials, studies of load environment, and studies of structural design and reliability. The concern for load environment warrants note; it is being recognized that one limitation in ability to predict fatigue behavior is lack of full understanding of loads due to gusts, maneuvers, landing impacts, ground operations, acoustic fields, etc.

A study of aircraft failures, sponsored by the U.S. Army[44], also indicates problems related to the current research. Of basic airframe failures in a sample of six types of aircraft, about 40 percent were ascribed to corrosion and fatigue. Factors noted for helicopters included cracking of rotor-blade hubs, separation of bonded metal joints on rotor blades, erosion of rotor-blade leading edges, and difficulties in sustaining rotor-blade balance. The U.S. Navy has had problems in carrier landings and takeoffs: with cables and arresting gear as well as with landing gear on the aircraft. An important point is that many problems are so concerned with specifics of design and service conditions that generalization is extremely difficult. Hence, much research is not readily generalizable toward application to other specific problems.

There are long-lifetime fatigue problems in other defense-oriented applications. One is in ground equipment, which includes track vehicles. In discussion of problems in this area with engineers at the U.S. Army Tank Automotive Center, the following impressions were received:

(1) The bulk of problems with suspensions are quality-control problems.

(2) There are some problems with such items as track pins and shoe bodies where there are uncertainties either in use of new materials (such as T-1 and HY steels) or in analysis of actual working stress values.

(3) There is interest, partly on account of improving damping of vibration, in composite materials including some of the foamed plastics.

The problem areas in such applications have been extremely difficult to classify on the basis of the information available in this survey.

Low-Cycle Fatigue

The generalities listed in the preceding section apply particularly to long-lifetime fatigue. For short-lifetime fatigue, the behavior of a particular material in an elastic-plastic condition becomes important. At the present state of knowledge, prediction of the fatigue behavior in this low-lifetime region requires direct tests of the material. There is some evidence that the fatigue strength is less sensitive to some of the parameters mentioned for long-lifetime fatigue. However, there is not yet agreement as to the best way to appraise a material for an application in which low-cycle fatigue may be important.

One area of current interest in low-cycle fatigue is that of fatigue cracking in cannon bores. In large-diameter (for example, 175-millimeter) gun tubes, it appears that small cracks develop in the rifling grooves near the breach end after a very few firings. Under subsequent firings, one or more of these may grow in length and in depth through the thick wall of the cannon bore. When this crack has grown to some critical depth, the next firing may cause rupture of the tube. Considerable effort has been expended at some of the arsenals in investigation of this process with the objective of greatly extending the number of firings of a particular cannon bore.[45] Current research includes:

(1) Fatigue studies of thick specimens of appropriate steels. These include emphasis on determination of crack depth growth; there is also consideration of means of delaying crack initiation (and/or early growth).

(2) Pressure cycling tests on gun tube sections. There is also consideration of future possibilities of hydraulic cycling in the field.

(3) Development of methods of nondestructive inspection appropriate for gun tubes. These include a rotating electromagnetic method and ultrasonic devices.

Long-range plans involve extensive studies of gun-tube materials and of processes(such as auto-frettage) in regard to fatigue resistance.

Low-cycle fatigue behavior is of concern in many pressure-vessel applications, ranging from turbine engine disks(46) to materials of interest for submersible vessels.(47) Many reports related to specific applications are restricted for proprietary reasons or by security classification. In general, there is current concern for more information on low-cycle fatigue behavior of many materials and under varied environments. One area of great interest to the U.S. Navy is that of HY steels, welded and in seawater.

Crack Propagation

Interest in fatigue-crack propagation characteristics of materials has been mentioned in the preceding section on empirical information. In service, the crack growth rate may be of outstanding concern, particularly in regard to time intervals for periodic inspection. This interval must be short enough that a crack just smaller than that detectable with whatever inspection means is used will not propagate to a size critical for the structural part during the time before the next inspection. Both the critical size and the propagation rate depend on the geometry of the part and the loads and environment as well as upon the material involved.

The large-bore gun tube mentioned with respect to low-cycle fatigue is one situation in which crack growth rates are of considerable engineering importance. In this situation it is recognized that small cracks may initiate after a very few rounds*. If the crack growth is slow, the cannon may have a long lifetime after the crack initiation; it is important to know this time as accurately as possible.

Wheels on large aircraft may have a long safe lifetime after detectable cracks. Here also it is important to have some knowledge of the rate of crack propagation.

Other instances might be listed where knowledge of crack propagation rates could be tied in directly with inspection. There is much current interest in both long-lifetime fatigue and in low-cycle fatigue in delineating the crack propagation portion of the total lifetime. This interest is particularly involved in the fail-safe design of aircraft.

Other Concerns

In a sense, the two areas of long-lifetime fatigue and low-cycle fatigue, with concern in each for the possible utility of separation of phases of crack initiation and crack propagation, cover the whole field of fatigue concerns. However, there are other classifications, consideration of which help delineate current problem areas.

Since most parts and components do not undergo constant-amplitude loading in service, there is continued concern in developing methods to allow for cumulative damage. One aspect of this concern is increasing emphasis upon trying to define service loadings with increasing sophistication. Some examples include: in aircraft--gust, maneuver, landing, and cabin pressurization loading; in track vehicles--impact, vibration, and maneuver loadings.

Another area of increasing concern is that of the influences of temperature -- thermal stresses, interaction with creep, effects of exposure (at no stress or under stress) -- on possible degradation of material properties. Such factors are of concern in many applications; different applications have different combinations of conditions so that generalization is difficult.

The influence of environment is an area of increasing concern in almost every application. The effect of aqueous surroundings is particularly important in Naval Applications and, to only somewhat lesser extent, in aircraft and even in ground vehicles. Practical considerations include surface treatments and protective coatings to mitigate corrosion fatigue and methods of inspection for incipient fatigue damage.

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*Some of the heat checks observed do not develop into fatigue cracks of major importance, so that it is not clear exactly what fraction of total lifetime is covered by the relatively regular growth called here "propagation". It is agreed that this stage may cover a major portion of the lifetime.

PREDICTION AND PREVENTION OF FATIGUE FAILURE

Prediction and prevention of fatigue failure in metals (and in other materials) is a very complex subject. The present state of the art leaves much to be desired with regard to the available knowledge, data, and information on fatigue and on the numerous relevant factors influencing the fatigue behavior of materials and structures. The situation is complicated further by the variabilities encountered in all aspects of the real, physical world. It is well known that material properties are not constant characteristics of a material, but they may vary within certain ranges. Even such a basic material property as mechanical tensile strength will vary among specimens made from supposedly the same materials and tested under supposedly the same testing conditions. The variability in material fatigue properties as determined on nominally identical laboratory specimens under nominally identical testing conditions is considerably higher than that of static material properties and, under certain conditions, this variability or "scatter" in terms of fatigue life may exceed two orders of magnitude.

When parts or structures are fabricated from the materials, additional variabilities are introduced by the manufacturing processes, and no two "nominally identical" parts are alike in all respects. The service or field use of such identical parts may also vary from part to part. The actual fatigue behavior of such parts in the service is influenced by all these factors and the associated variabilities, and it is nearly impossible to pre-determine accurately the fatigue life of a given specific part even under given use conditions. Often, however, the exact use conditions are not known beforehand.

The above explains why it is so difficult to design parts and structures for fatigue applications. In some cases it is possible, at least in principle, to provide quite "safe" designs against fatigue failure simply by overdesigning the parts and structures. This can be achieved by purposely overestimating the expected loads and by keeping the design stresses at very low levels as compared with those stresses at which fatigue failure might occur, taking into consideration, of course, all those factors that might have influence on the fatigue strength of the part or the structure. In a majority of cases, however, such an approach is impractical or even impossible. For example, an aircraft designed with such a philosophy would not be an aircraft, because it would be too heavy to leave the ground. Generally speaking, today's technological and economic considerations dictate that any system, device, or structure be designed to perform its function effectively at a minimum cost and with a high degree of reliability, and often also at a minimum weight and within a limited space. These considerations impose demands on the design of a structure that force the designer to compromise or to make tradeoffs among these factors.

There are basically three approaches used in the design and utilization of structures subjected to fatigue loading and in the prevention and/or prediction of fatigue failure: the analytical approach, the experimental approach, and planned inspections and/or monitoring of the structures during their service life. In critical applications, all three approaches are often employed.

The purely analytical approach to the design of structures for fatigue has severe limitations if used by itself and if an optimum design is to be developed. Because of the insufficient knowledge of fatigue and generally insufficient data, many assumptions and approximations have to be made and these prevent making accurate estimates of the fatigue strengths or the expected fatigue life. A purely analytical approach may be used in noncritical applications, where a fatigue failure is of little consequence (except, perhaps, being a nuisance), in applications where an overdesign can be tolerated, and in some very simple cases for which the available information might be sufficient. For critical and/or complex structures, the analytical approach is often used for developing the preliminary designs. Prototypes or special test pieces are then constructed and fatigue tested. Once experimental results (fatigue failures) are obtained, the analytical methods constitute a powerful tool for analyzing those results and for improving the designs.

Experimental approach to fatigue design and prediction involves various types of testing, such as simple specimen tests on standard fatigue-testing machines in the laboratory, testing of parts and components (either on standard fatigue machines or on specially designed test setups), testing of components or structures under simulated field conditions, and testing of the structures under actual field conditions. The experience gained from service failures adds considerably to the existing empirical knowledge on fatigue even though this experience is the one we are trying to avoid because it has usually undesired consequences such as breakdown of equipment, unforeseen expenditures, loss of time, and sometimes loss of the entire equipment and human lives.

Any experimental fatigue program is expensive and time-consuming and there are practical limitations in both cost and time that can be devoted to each specific investigation or to a development program. Because of the variabilities or scatter in fatigue strength and in fatigue life, a certain number of nominally identical specimens or structures have to be tested to obtain the desired information on their fatigue behavior and on the variability or scatter to be expected. In practice, it is seldom possible to test a sufficiently large sample of identical structures to obtain statistically significant results with a high confidence. Therefore, a certain amount of judgment is almost always needed when experimental results are interpreted and utilized in making design and engineering decisions.

As already mentioned, it is impossible to predict accurately the fatigue life of a given part or structure in service, even if the best known analytical methods and all the available data and information are employed and supplemented by experimental testing and/or development programs. Because of the variabilities involved, some of the parts or structures may fail much sooner than others and some may have, for all practical purposes, an infinite life, depending on the application. If the "design" service life is established for a high reliability, that is such that the probability of a fatigue failure within this life period is small, most of the parts or structures will be replaced or retired long before the end of their useful life. Moreover, this approach still does not guarantee the absence of fatigue failures. Such failures may occasionally occur because a particular part or structure is

extremely "weak" as compared with the others, or it had a defect not detected during manufacturing and inspection processes it had been subjected to some extreme service conditions and service abuse.

These problems can be overcome to a degree in many applications by employing various inspection methods and monitoring techniques during the service life of parts and structures. The objective is to detect an incipient fatigue failure before it occurs, so that the part or structure can be repaired or replaced in time to avoid a catastrophic failure. In principle, such an approach, if applicable and properly used, has several advantages:

(1) It can and does decrease the incidence of catastrophic failures.

(2) It increases the operational reliability of the structures and equipment.

(3) It permits the use of less conservative designs which usually results in savings of weight, space, and initial cost.

(4) It allows a better utilization of the structures by extending their actual service life until shortly before an incipient failure instead of retiring a structure at some predetermined time which, in many cases, would represent only a fraction of the structure's available useful life.

On the other hand, any inspection consumes time and costs and, depending on the method used, it may involve rather complex and expensive equipment. In many cases, the equipment cannot be used while being inspected. There are also some limitations and some complicating factors associated with each inspection method, as will be discussed later. In practice, therefore, it is often a question of tradeoffs as to how much and what type of inspection can and should be done.

The prediction and prevention of fatigue failure of a part or structure by means of inspections depends obviously on the ability of the inspection method(s) to detect an incipient fatigue failure. In other words, the inspections of a structure should yield a positive identification of the fatigue damage that it has already incurred and that would eventually lead to failure. These inspection methods should be, of course, of a nondestructive type so that they would not do any damage to the items being inspected and would not affect their fatigue life. Before considering the various available and potential nondestructive inspection (NDI) methods for detecting fatigue damage, some relevant factors are reiterated and briefly discussed below.

The process of fatigue, as already mentioned, can be considered as consisting of three phases:

(1) Initial fatigue damage leading to a crack initiation

(2) Crack propagation until the remaining uncracked cross section of a part or a structure becomes too weak to carry the loads imposed upon it

(3) Final, sudden fracture of the remaining cross section.

The initial fatigue damage starts early in the life of a part subjected to a fatigue loading. Under certain conditions this may occur upon the application of the first or of the first few load cycles. Such damage may start at several locations either simultaneously or in some sequence. Upon application of additional load cycles, microcracks may develop in some (but not necessarily all) locations of the initial damage. These microcracks grow until a fatigue macrocrack or several such cracks develop. These, then, propagate at certain rates (depending on the conditions) until the final fracture occurs. It should be noted that usually there is one major crack that causes the final fracture, even though there are cases when several cracks join into a larger crack before the final fracture occurs. It should also be noted that sometimes a fatigue crack may stop propagating because of stress redistribution caused by this crack or by other factors. Such a so-called nonpropagating crack would not cause, by itself, a fatigue failure (final fracture).

The transition from the initial fatigue damage to microcracks and, then to fatigue macrocracks, is somewhat subtle and difficult to define. For the purposes of discussing the nondestructive inspection (NDI) approaches to the detection of fatigue damage, it is assumed that the crack-initiation phase is the one during which a crack cannot be detected, whereas the ability to detect the initial (small) fatigue crack characterizes the beginning of the crack-propagation phase. In order to predict and prevent a fatigue failure, the fatigue damage should be detected either during the crack-initiation or during the crack-propagation phase. The fatigue-crack propagation rate usually increases with the crack length or size and it is, therefore, desirable to detect an incipient failure as early as possible.

Because a fatigue failure starts usually at or near the surfaces, only the surfaces at critical locations of parts and structures have to be inspected. In some applications, it might suffice to inspect only one or a few critical locations. In other cases, several locations and/or larger surface areas must be inspected.

NONDESTRUCTIVE INSPECTION (NDI) METHODS AND APPROACHES FOR DETECTION OF FATIGUE DAMAGE

Information on the application of NDI methods to the detection of fatigue damage is scattered throughout both the fatigue literature and the literature on nondestructive testing, and there are relatively few publications that deal with it specifically. Most of the latter are limited to descriptions of laboratory investigations and cover the application of one or several existing or potential NDI methods to fatigue testing under controlled laboratory conditions. In many of these cases, the main objective is to study the fatigue mechanism. The NDI methods are utilized, are modified and improved, or new approaches are tried primarily for this purpose. Even though such investigations do contribute considerably to the available knowledge and sometimes result in developments that eventually lead to new or improved NDI methods for field use, there is a great difference between what can be done

in the laboratory and what can be used in practical applications under field and service conditions.

There appears to be a lack of general review and assessment on the overall situation with regard to the use of the various NDI methods in the detection of fatigue damage, particularly in field and service use. The NDI approaches to the detection of fatigue damage are described below only in a general, qualitative way covering briefly some of the NDI methods that are well established and some that are being developed, have been tried, or are being explored.

The many NDI methods already existing or those potentially useful that could be applied, at least in principle, to the detection of fatigue damage can be classified in several ways:

(1) According to the physical phenomena utilized or the type of energy employed

(2) According to their capability to detect damage at different stages of the fatigue process; i.e., those that can detect initial fatigue damage, those that can detect fatigue damage only after a visible crack has developed, and those whose capability lies between these two

(3) According to their capability to inspect entire parts and surfaces or specific locations only

(4) According to their ability to provide inspection (or "monitoring") on a continuous basis or requiring that the inspections be conducted periodically at certain time intervals

(5) According to their present usefulness, state of development, and applicability; i.e., those that are already being used under field and service conditions, those that are used for laboratory and research work only, those that are being developed at the present time and show some promise to become useful in the future, and those of a purely academic interest. It should be noted that all the NDI methods that are used in the field can, of course, be used also in the laboratory either in their usual established form or in some improved or modified form adapted for the purposes of the laboratory or research investigation on hand.

Because the main purpose of this survey is to review some problem areas in prevention of fatigue failure in structures under field and service conditions, first the NDI methods that are already in field and service use are briefly described below. Subsequently, some other possible NDI approaches to the detection of fatigue damage and some recent attempts to develop so-called "fatigue damage indicators" are reviewed. Finally, a brief assessment of the current situation with regard to the use of NDI methods for the detection of fatigue damage is presented.

NDI Methods in Field and Service Use

Most of the NDI methods that are used under field and service conditions are those that are capable of detecting fatigue cracks of various sizes. These methods are described in books on the subject of nondestructive testing [e.g., References (48) and (49), both of which contain numerous additional references] and various other publications such as reports, technical papers, and magazine articles [e.g., References (50) and (51)]. A good source for bibliographical information on the subject of nondestructive testing is the Non-Destructive Testing and Information Center at the Army Mechanics and Materials Research Center. In principle, any nondestructive testing method that is capable of detecting surface imperfections and cracks can be used as an NDI method for the detection of fatigue cracks. The NDI methods most commonly used in the field and service for fatigue-crack detection are described separately below. All of them are covered in References (48) and (49). Additional references relevant to the individual methods are cited in the text when appropriate.

Visual Inspection

Visual inspection is the oldest, simplest, cheapest, and the most widely used of all the NDI methods for the detection of fatigue cracks. The basic principle used in visual inspection is to illuminate the object and examine the surface with the eye or with light-sensitive devices such as photocells or phototubes. The surfaces should be adequately cleaned before being inspected. Visual inspection for the detection of fatigue cracks can be improved by optical aids such as mirrors, lenses, microscopes, periscopes, and telescopes. These optical devices compensate for the limitations of the human eye and/or provide a magnification of the areas to be inspected. Enlarging projectors provide means for improving viewing conditions for inspection of small parts. Borescopes permit direct visual inspection of the interior of hollow tubes, chambers, and other internal surfaces. Photoelectric and other light-sensitive systems can sometimes be used to replace direct visual inspection and compensate for errors due to operator fatigue.

The capability of visual inspection to detect a fatigue crack depends on many factors such as the size and location of the crack, the illumination used, the optical aids employed, and the skills of the inspector. It is often difficult to detect even a relatively large fatigue crack that is located, for example, at the corner of a groove or that coincides with a machining mark. There are, of course, also limitations on the size of cracks that can be detected by visual inspection, depending on the optical aids employed.

Liquid Penetrants

The liquid-penetrant method is one of the oldest methods of nondestructive inspection and it is capable of detecting fatigue cracks that may be impossible to find with the most careful visual inspection either because they are too small or because they are difficult to discriminate due to their location. Thus, in a sense, it is an aid to visual inspection. The principle involves applying to the surface a liquid having a low-surface tension and low viscosity. Used on a clean surface that

the liquid will wet, the liquid is drawn into the cracks by capillary action. The presence of the penetrant in the cracks is revealed when, after wiping the excess penetrant from the surface, a developer is applied that acts like a blotter and draws the liquid out. There are two types of penetrants in general use. One contains a dye which usually gives a good color contrast against the selected developer. The other contains dissolved fluorescent material which makes it readily visible when viewed under near-ultraviolet light or so-called "black light". The wavelength of this light is just outside the visible range on the blue or violet side and it is not in the chemically active ultraviolet range.

In addition to References (48) and (49), a good source of information on the various aspects of the liquid-penetrant methods is the book by Carl E. Betz [52], which contains also a bibliography. Liquid-penetrant inspection is inexpensive and readily applicable to field use. It has the requirement that the surfaces must be cleaned before the inspection and also afterward to remove the developer. It can be applied to any nonporous material.

Magnetic Methods

Magnetic inspection methods are used to detect surface or near-surface discontinuities in ferromagnetic materials and they are well suited for the detection of fatigue cracks. The principle employed here is that once a magnetic field is induced in a material, any cracks and flaws that are present will perturb or distort that magnetic field. This perturbation, fringing, or so-called "leakage flux" is then detected and measured. These methods are most sensitive when the crack orientation and the magnetic field direction are perpendicular to each other. When they are parallel, the crack will not be detected.

The magnetic-particle method is the most frequently used. It consists of three basic steps: (1) establishment of a magnetic field in the object to the inspected, (2) application of magnetic particles to the surfaces of the object, and (3) visual examination of the surfaces for indications of fatigue cracks. These indications are provided by the particles being attracted to the locations of the cracks (or other defects) due to the local variations in the magnetic field that are produced. Two classes of magnetic particles are available. The wet-method particles use a liquid vehicle; the dry-method particles are borne by air. These particles are usually colored to give contrast with the surface being inspected or coated with fluorescent material to make them readily visible under black light. Parts inspected by magnetic-particle methods must be cleaned. If dry particles are used, the part must be dry as well as clean.

There are other possiblities to detect the presence of a leakage flux. In principle, this could be accomplished even with a simple compass by moving it over the surface of a magnetized part. Such a method is, of course, too insensitive and too clumsy for practical applications. The magnetic methods in use in various applications are based mostly upon the generator principle employing current-carrying coils and probes for the detection of the magnetic field perturbations or the leakage flux. Some other approaches, e.g., such as the use of the Hall-effect element, have also been employed. A considerable effort has been devoted in recent years toward further development and refinement of magnetic inspection methods for various specific applications for the detection of fatigue damage, and for the study of fatigue mechanisms. Many of these investigations have been carried out or supported by the Army, Navy, and Air Force. Examples of such investigations are given in References (53) through (59).

Radiography

Radiography is a method of nondestructive inspection which uses X-ray, gamma, beta, or neutron radiation. It is based on the ability of these radiation sources to penetrate materials. The intensity of the penetrating radiation is modified by passage through material and by defects in the material. These intensity changes are recorded on film as areas of varying density (or darkness) which permit distinguishing flaws or cracks. Obviously, maximum sensitivity occurs when the crack is oriented such that its longest dimension is parallel to the direction of radiation. The radiographic techniques are capable of detecting a defect (crack) that may be less than 1 percent of the thickness of the object (under special, favorable conditions).

X-ray radiography has two main advantages: versatility and sensitivity. The energy of an X-ray source can easily be adjusted for variations in thickness. It is also adaptable to fluoroscopy and television systems. The advantages of gamma radiography are portability and a relatively low cost. The portability comes from the fact that the source is small, and needs no electric power or cooling water. This permits its effective use in the field, particularly in remote areas. One of the difficulties with radioactive sources, however, is that the source can never be varied or turned off, so that safety precautions must be observed at all times. (X-rays constitute a health hazard only during the operation of tho equipment.) Conventional radiography is firmly established and reasonably easy to understand. One of the original drawbacks, the long time involved in developing and processing of film, is lately being overcome by modern automatic film-processing equipment and by special techniques such as Xeroradiography and the Polaroid process.

Additional information on radiography can be found in References (60) through (63).

Ultrasonics

Ultrasonic methods have recently achieved wide employment in many applications and they are widely described in the literature [e.g., References (64) and (65)]. Because ultrasonic waves are based on mechanical phenomena, they are particularly useful for determining the integrity and structure of materials. Basically, sound energy above the audible range is transmitted into a part and a signal is received and analyzed. The ultrasound is transmitted and received by transducers. The transducer is placed upon the part to be inspected. Coupling of the transducer to the part is one of the most critical aspects of ultrasonic inspection. It is usually achieved by the application of liquid of various types at the transducer-part interface. The part is sometimes immersed into a tank of water to insure good coupling.

The ultrasonic beams may be examined in terms of through-transmission or reflection. It is also possible to determine resonance frequency of the material under test. The receiving transducer may be a separate unit (through-transmission technique) or it may be the same transducer that sent the signal (reflection and resonance techniques). For crack detection, the reflection technique (sometimes called the pulse-echo technique) is most commonly used because it usually permits the determination of the location of the crack, wherever it might be within the part, and because only one transducer on one side of the part is needed. When a pulse of ultrasonic energy is sent into the part, a discontinuity (e.g., a crack) in its path or any boundary of the part on which it impinges will both absorb and reflect the energy. A defect (crack) can be recognized by the relative time for return of the echo or reflected energy to the transducer. In the through-transmission technique, a similar pulse of ultrasonic energy is sent into the part, but here the presence of a crack is detected by the energy lost or absorbed by the crack as revealed by the second, receiving transducer. The resonance technique is used primarily for measuring thickness, Young's modulus, and damping capacity, and is less important in fatigue-crack detection.

In addition to the above three techniques, the versatility of ultrasonic methods is further enhanced by the possible choice of several types of ultrasonic waves. Depending on the angle of the incident beam, longitudinal, shear, Lamb (or plate), and so-called Rayleigh (or surface) waves may be employed. Since fatigue cracks usually originate at the surfaces, the Rayleigh surface waves are particularly suitable for detecting fatigue cracks. However, depending on the part geometry, the application, and other factors, all the other wave forms might be useful under certain circumstances for fatigue-crack detection.

The ultrasonic methods now available are rapid, economical, and sensitive, and can have good accuracy for determining crack extent and position. They have good penetrating power for examining thick sections of most homogeneous materials, and often access to only one surface of the part is required. Equipment is light and portable so that on-site inspections are possible. With all these advantages, there are conditions which can limit the usefulness of ultrasonic inspection. These include unfavorable part geometry (such as complexity, contour, and size), orientation of the cracks, and misleading responses that may occasionally be obtained. Also, ultrasonic inspection, as presently practiced, depends upon the experience, skill, and judgment of the inspector. He must interpret, in terms of crack size and location, the very indirect evidence presented by the electronic equipment. He must be able to distinguish between significant signals and spurious ones caused by scatter, noise, and multiple echoes.

Because of the versatility of ultrasonic inspection methods, they have been recently widely employed in various fatigue laboratory investigations to study the fatigue mechanism as well as to develop these methods further for the detection of fatigue damage in the field. Examples of such investigations are given in References (57) through (59) and (66) through (72).

Eddy Current

The eddy-current method is a comparatively recent nondestructive inspection technique. It is being frequently used for nonmagnetic materials. (It can also be used for magnetic materials, but these require more complex systems). The principle involved is simple. When a coil that is carrying a high-frequency alternating current is brought into the vicinity of an electrical conductor, eddy or induced currents are generated in the conductor. A magnetic field associated with the induced currents is created. Flaws, cracks, and various other inhomogeneities cause resistivity changes within the part. These, in turn, affect the induced currents, and consequently, the magnetic field produced by them. Detection and measurement of the magnetic field form the basis of the inspection.

Two general types of coils are in common use. One is the circumferential coil through which a part passes; it inspects a volume of material within the coil that is determined by the coil geometry. The second type is so-called probe coil or point probe which is usually small and is placed on the surface of the part to be inspected such that the axis of the coil is perpendicular to the surface. It inspects only a volume of material beneath it that is essentially equal to its cross section times the depth of penetration. Each type of coil can be made in a number of designs, depending on the application. Some applications use a single coil whose electrical properties reflect the eddy current information; other systems use primary and secondary coils.

There is a variety of eddy-current inspection instruments having various degrees of versatility. Many of them are portable. Once proven for a specific application, eddy-current instruments do not require skilled operators and the inspection process is quite rapid. In some applications, the eddy-current inspection method has been used very successfully for fatigue-crack detection. On the other hand, eddy-current inspection methods are sensitive to many variables that may influence the electrical characteristics of the system and the results obtained. Also, the signals obtained are sometimes of a comparative nature and reference standards are often needed to interpret the results. Eddy-current inspection methods are widely described in the literature; References (73) through (78) represent a few examples.

NDI Methods for Specific Applications

The above six major NDI methods for fatigue-crack detection are in general use. They can be employed in many applications, even though there may be cases when none of these methods is really suited for a particular application. Some individual applications may require that these methods be modified, extended, specially adapted, or combined for the purposes on hand. There are also some individual applications where other NDI methods can be successfully employed, as is briefly discussed below.

One of the oldest NDI methods for detecting the presence of cracks is the sonic test. It consists of striking the object with a sharp blow and listening for its characteristic vibrations. This

practice is still quite common in service checks of railroad-car and locomotive wheels where its purpose is to detect cracked wheels. Electrically or pneumatically driven hammers or tappers, together with stethoscopes, have been used for checking some castings, forgings, and weldments. Unusual sounds in rotating or moving machinery have often served as warnings of the impending failure of a part or component. In recent times, sonic tests have been supplemented by various instrumentation and readout devices to increase their sensitivity, range, and versatility.

Somewhat related to the sonic tests are some vibration tests involving frequency and damping. After the object is excited, either the natural frequency or damping is observed. A large crack may change the natural frequency noticeably. Damping or rapid decay in vibrational amplitudes is often a good indicator of the presence of cracks.

Another NDI method, developed for a specific application, is the electric-current test of railroad rails [Reference (48), p 35-11]. Specially designed railroad cars are equipped to locate transverse rail fissures caused by fatigue, by passing a heavy electric current through the length of the rail. This longitudinal current flow is distorted where transverse cracks intercept its path. Since steel rails are ferromagnetic, the magnetic field produced by the distorted current path is detected by pick-up coils sliding over the smooth surface of the rail top.

In some cases, it is possible to detect the presence of a fatigue crack in an object by measuring the changes in electrical resistivity of this object. In some other cases, when a structure can be pressurized, the presence of a crack can be detected by the loss of pressure and/or by detecting leakage. In cases when the usual location of cracks is well known, replicas of the surface at this location can be made periodically and examined for indications of cracks under an optical or an electron microscope. This latter approach permits one to follow the propagation of a crack over a time period. Generally speaking, there are many possibilities of special, limited-use NDI methods that can be used, developed, and adapted for specific individual applications. The above represent only a few examples.

Other NDI Approaches to Fatigue-Damage Detection

In addition to the continuous effort to improve and to refine the NDI methods that are already in use under field and service conditions, there have been many attempts to develop new approaches to the detection of fatigue damage. These attempts have been so far limited mainly to laboratory investigations. A few of them show some promise of eventual usefulness while others do not appear, at least at the present time, to have the potential to become practical methods for field use, even though they might be useful for studying the fatigue mechanism and for fatigue-damage detection under controlled laboratory conditions. Examples of such new approaches, to the extent they were uncovered during the present survey, are briefly discussed below.

Reference (79) describes two experimental feasibility investigations of nuclear methods for the detection of incipient fatigue failures in aluminum. The first investigation involved the beta-radiation detector. This method did not show a sufficient sensitivity. The second investigation involved a radio-autographic method based on the liquid-penetrant principle. A radioactive solution was used as the penetrant. Although the experiments had shown that this nuclear method is applicable to the detection of minute fatigue cracks, it did not appear to have any advantages over the liquid-penetrant methods in common use. It was, therefore, recommended that no further research be done along these lines.

It has been frequently observed in laboratory investigations that heat is generated by a developing crack. Detection of this heat during fatigue loading could, therefore, serve as an indicator of an incipient fatigue failure. An analytical feasibility study (80) has indicated that there may be an instantaneous temperature rise on the surface of a slip band of a few degrees centigrade when a group of dislocations breaks through and that it might be possible to detect such temperature differences either by thermally sensitive films or by infrared microscopy. This approach, if developed, might be capable of detecting an early fatigue damage. A growing crack generates more heat and its detection with appropriate heat-sensing devices could be even easier. Such passive systems that rely on the heat generated by a developing crack can, of course, be employed only while the part of specimen is subjected to fatigue loading. Another approach is to employ an active system that injects heat energy and detects temperature changes caused by the change in thermal conductivity due to a developing crack. Such a system has been developed (81-82) for fatigue-crack detection and has been used in a sonic test facility of the Air Force. This system has the advantages of allowing control of heat input and the ability to inspect samples both with and without fatigue-test excitation. It operates on the scanning principle, utilizes a radiative heat source, and infrared techniques, and inspects the surfaces from a distance. The surface and near surface cracks which the system detects can also be found by dye penetrants and eddy currents.

Reference (83) describes some research efforts directed toward the utilization of acoustic emission in the study of fatigue mechanism. It has been observed that metals emit squeaking and popping noises when subjected to external loads. These sounds, however, are usually above the frequency range of the human ear and are very weak. Special acoustic detection devices such as piezoelectric sensors must, therefore, be used and the surrounding must be quiet. Noise isolation is a major problem. Acoustic emission signals smaller than twice the system's electrical noise are lost in the analysis. Loads must be applied slowly and quietly which requires special laboratory equipment. Under proper laboratory conditions, acoustic emission might be useful for studies of microscopic deformation phenomena, crack initiation, and crack propagation. Reference (84) describes a study of crack propagation in aluminum specimens during monotonic tension that employed an acoustic detection method. Another study on acoustic emission is

reportedly being carried out presently under ARPA's sponsorship. Although acoustic emission appears to be a promising approach for laboratory studies, its usefulness as a potential NDI method for the detection of fatigue damage in the field will depend to a large degree on whether or not it will be possible to develop techniques for obtaining sufficiently large acoustic-emission signal to noise ratios under operating conditions.

Exoelectric emission is another phenomenon that has recently received some attention as a possible approach to the detection of fatigue damage. The emission of exoelectrons from aluminum during fatigue was studied by J. C. Grosskreutz and D. K. Benson (85) in 1961-1963. They concluded that this approach to the monitoring of fatigue damage did not appear to be feasible at that time. Presently, an investigation on exoelectric emission is under way at the Cornell Aeronautical Laboratory, Inc., under the sponsorship of the Army. This investigation involves (1) the use of a phosphor coating and (2) the use of a photographic emulsion, with the latter being tried first. The mechanism of the exoelectric emission effect is not known with certainty. It has been speculated that dislocations at the surface expose raw material and enhance local emission which, if detected, might serve as an indicator of fatigue damage. The results of this investigation are not yet complete. Another investigation on exoelectric emission is reportedly being carried out presently under ARPA's sponsorship.

An investigation (sponsored by the Army) of the feasibility of a new approach to the detection of fatigue damage is currently being carried out by the Industrial Nucleonics Corporation with the cooperation of Battelle Memorial Institute. This approach involves impregnation of a radioactive gas into the surface layers of fatigue specimens and detection of changes in emission characteristics of this gas after the specimens have been subjected to fatigue loading. Autoradiography has shown significant increases in emission at the location of fatigue damage in steel specimens at a relatively early state. This work in continuing.

Two other current investigations on potential NDI methods for the detection of fatigue damage, sponsored by the Army, involve the use of laser interferometry and inductive sensing of changes in paramagnetic properties. Another investigation involving laser and acoustic holography is being supported by ARPA. The results of these investigations are unavailable at this time.

Fatigue-Damage Indicators

In addition to the NDI methods that are usually employed periodically, there have been several attempts to develop warning or monitoring techniques that would be capable of providing an advance warning of an incipient fatigue failure on a continuous basis. One such technique was described by H.W. Foster (86) as early as 1947 and it has been used in testing full-size aircraft structures. It consists of cementing small insulated wires to the most critical areas of the structure perpendicular to the direction of the expected cracks. The crack is then indicated by rupture of the wire, which is incorporated in a suitable circuit to provide a warning signal. This method can detect only cracks sufficiently large to cause a breakage in the wire. There are many factors to be considered with regard to the strength properties and dimensions of the wire, the insulation and the cement used, the installation technique, and the location and orientation of the wires.

Another approach to monitoring fatigue damage in structures is described in Reference (87). It involves the use of so-called monitoring strips that are attached to a structure and that are designed to fail before the structure. These strips are made of thin material and are provided with reduced areas containing stress concentrations such as notches and holes. Portions of the full-width strip lengths are bonded to the structures, whereas the areas in the vicinity of the reduced sections remain unbonded. The strips at the notched region operate at higher strains than the structure to which they are attached. If properly designed and installed, these strips fail in advance of the structure by approximately predetermined time periods or numbers of cycles, depending on the strain magnification provided and depending on some other relevant factors involved. The failure of the strips can be detected either visually upon inspection or from an electrical signal if they are combined with small wires incorporated in a circuit that break together with the strips. Because of the many factors involved, the failures of the monitoring strips are correlated with the structural failures by means of fatigue testing. Once the correlation is established, such monitoring strips can serve, at least in principle, as warning devices of an impending fatigue failure for the particular structures for which the correlation has been established. There are, however, many complicating factors, and this survey did not uncover any information with regard to the actual current field use, if any, of such monitoring strips, except that this approach has been tried.

A quite recent development in the area of fatigue damage indicators is the "Fatigue-Life Gage". Reference (88) describes this gage, the underlying principles, and the initial development effects. This gage resembles a common foil-type strain gage. When it is bonded to a critical area of a structure, using standard techniques, the fatigue loading of the structure, whether in a cyclic or random manner, causes a permanent increase in the resistance of the gage. The magnitude of this change is a function of the load spectrum applied to the structure. When a correlation between the resistance change and fatigue life of the structure is established by experiments, the new gage can provide an indication of the fatigue life consumed and of the fatigue life remaining in the structure. The gage operates regardless of the presence or absence of electrical connections to it, and its output (change in resistance) may be measured continuously or intermittently, as desired. The main difference between the fatigue gage and the standard foil gage lies in the fact that the fatigue gage is designed to specifically maximize the change in its resistance under repeated load applications, whereas in standard gages the objective is to minimize this change. The new concept shows some promise, but as is stated in Reference (88), it is not yet fully developed and should be regarded only as an experimental item at the present. Considerable effort is required to develop fatigue gages for various

applications, on various materials, and under various conditions. There are many complicating factors involved which create practical difficulties. Examples of additional development efforts along these lines are given in References (89) and (90).

In contrast to the NDI methods which detect the fatigue damage in the structure or part itself, the three above types of monitoring devices provide an indication of a fatigue damage indirectly by employing a secondary element that is attached or bonded to the surfaces at selected locations. A failure of the bond would make these devices inoperative. Another limitation is the fact that these devices can be attached only to smooth surfaces which are often not the most critical locations at which fatigue cracks initiate. Therefore, an experimental correlation involving testing is frequently needed to establish the relation between the behavior of these monitoring devices located in the vicinity of a critical location and the failure occurring at these critical locations.

Fatigue-Damage Detection Under Field and Service Conditions

The above review was limited to nondestructive approaches to fatigue-damage detection that are either used in the field already or that have been considered as potentially useful, even though some of the latter may never be developed to a degree of being practical NDI methods for field and service use. It should be noted that there are other methods, not mentioned above, that can be used for fatigue-damage detection under laboratory conditions. The most powerful method of detecting damage at a very early state of the fatigue process involves the use of electron microscopy, which usually requires the destruction of the test specimen. Some other methods (e.g., such as X-ray diffraction analysis) can also be employed in the laboratory to study the fatigue mechanism. As mentioned already, however, there is a great difference between the detection of fatigue damage in the laboratory and under field or service conditions. Of the various NDI approaches reviewed above, other than those that are already in field use, none appears to be readily adaptable to various field applications in the near future. The fatigue damage indicators also do not appear to be in general field use at present. Therefore, the remainder of this discussion is limited to the field application of the existing NDI methods that are capable of detecting fatigue cracks of various sizes.

In the application of any NDI method for the prediction and prevention of a failure, the important considerations are what to inspect, where (what locations) to inspect, when to inspect, how to inspect, and how to interpret the results of the inspection. The parts or structures that are subjected to fatigue loading and their critical locations are usually known from the design considerations or from previous experience. Most of the inspection methods in field use require that the surfaces to be inspected be accessible. This often requires disassembly of components to expose the critical location and surfaces of parts. Disassembly and assembly of components might sometimes be a cause of subsequent failures because of human error. Sometimes such disassembly and assembly are quite involved and some components, such as riveted structures or press-fitted parts, cannot be disassembled without destroying the joints. The latter might damage the joined parts. Additional difficulties may arise if the design of a part (e.g., a casting) is such that the critical locations are inaccessible. It is, therefore, a good practice to design fatigue sensitive parts and structures in such a manner that the critical locations would be accessible for inspection.

The establishment of inspection period is another problem. Although attempts have been made to develop fatigue-damage indicators or monitors to provide a warning of an incipient failure on a continuous basis, almost all inspection methods used routinely in the field today are still those that are employed periodically in accordance with some schedules. The establishment of these schedules, whether at fixed or varying intervals, is based on several considerations such as the required reliability of the equipment, the consequences of a failure, costs involved in an inspection, and the time lost or the equipment unavailability during the inspection. From the economical and operational points of view, the periods between inspections should be as long as possible. To prevent the occurrence of a fatigue failure, however, these periods should be short enough to assure that a fatigue damage that either is detected and is small or remains undetected during an inspection would not progress to a fatigue failure (fracture) before the next inspection. Therefore, if the fatigue damage can be detected earlier, the periods between inspections can be longer. The optimum frequency of inspections for a given application depends also on the fatigue-crack propagation rates for this particular application. As was discussed earlier, a considerable amount of both theoretical and experimental work has been conducted on fatigue-crack propagation and practical experience has been gained in many applications. In many cases the crack-propagation phase constitutes the major portion of the fatigue life of a part. In these cases, it would be uneconomical to replace the part as soon as a tiny fatigue crack is observed if the part is still capable of performing its function for a considerable time. Here, the inspection period should be established, based on the available knowledge, so that the next inspection would be performed before the crack could grow to a critical size. Obviously, the larger is the observed crack, the shorter should be the interval to the next inspection. In applications where the fatigue-crack propagation rates are known to be high, it may be better to replace or to repair the part as soon as a fatigue crack is detected than to schedule another inspection after a very short time period.

With regard to the question as to how to inspect and which of the NDI methods to use, there are no generally valid answers. There is not a single, universally useful NDI method that could be applied to all materials, all situations and their specific requirements, and all applications. Rather, there are several NDI methods and techniques, each having its advantages, limitations, and complicating factors. The problem is to select the right method for the application and to apply it correctly. This selection may depend on the application itself, on the materials, on the available NDI equipment, on the available experience and skills, on costs of the inspection, and on other factors.

The visual inspection method is by far the most widely used. Even when the presence of a

fatigue crack is first detected by some other NDI method, the final evaluation and assessment of this crack is often done by visual means, supplemented by optical aids. It is helpful, under certain circumstances, to subject the surfaces to be inspected to a tension load. This opens the cracks which might otherwise be tightly closed and difficult to find. The liquid penetrant and magnetic particle inspection methods can be considered, in a sense, as extensions of the visual inspection method in that they give a direct indication of the presence of a crack.

NDI methods such as magnetic (other than magnetic particles), radiographic, ultrasonic, and eddy current provide a signal or readout which has to be interpreted in terms of the incurred fatigue damage (unless supplemented by visual inspection). This often has to be done by inference, which may lead to errors in interpretation. Therefore, the use of these NDI methods, as well as all the others, requires certain skills and experience and the field of NDI is still an art as well as technology and science.

Despite the availability of several NDI methods, there are still applications where these methods are difficult to employ and cases where the application of NDI proves to be unfeasible because of the practical difficulties encountered. This explains the continuous development efforts directed toward improving the existing NDI methods, toward making them more versatile, and toward developing new methods. It should also be noted that some applications require that the existing methods be modified or some special NDI methods be developed for these particular applications.

CONCLUSIONS AND RECOMMENDATIONS

An observation by an attendee at the 1967 International Committee on Aeronautical Fatigue (ICAF) meeting was that the U. S. effort in the area of fatigue of materials and structures is enormous so that "the U.S. representative had limited success in providing a full picture (of just recent developments with respect to aircraft) simply due to volume". This increasing volume of data presents one outstanding area of concern in regard to full utilization of existing knowledge. As indicated earlier, there are continuing efforts, particularly with respect to materials widely used in aircraft, to collect and assess and present material fatigue properties. In some other areas, such as structural steels, there are less adequate compilations. Providing a reasonably complete, up-to-date, carefully evaluated, well-arranged fatigue-data collection is an immense task but seems a real need.

Many gaps exist in present information. These include (but are not limited to): lack of data on some materials and their processing, lack of data for some conditions of loading (for example, under spectra of many levels), lack of engineering understanding of the stages of crack initiation and crack propagation, and lack of information on interactions of material with environment (such as temperature and surrounding fluids). Almost any such gap in engineering information is important to some applications. Priorities in effort to fill in these gaps depend on many factors which are outside the scope of the survey. It has even been impossible to estimate technical needs in any depth on account of lack of the extensive information on service problems that would be necessary to form valid judgments. Some areas that are receiving much attention are: fatigue-crack propagation and fracture, low-cycle fatigue, analysis of load environments, influence of metallurgical variables, and methods of crack and/or damage detection.

The very many parameters that have been shown to affect fatigue behavior influence the approaches and methodology of inspection to detect incipient damage. One concern is whether detection of a very small crack will be valuable in a specific situation or whether it is urgent, in that situation, to detect damage prior to the existence of a small crack. Another concern is the necessary frequency of inspection in view of service requirements. It is important to keep in mind that different types of processing and different kinds of surfacing and different types of stressing affect the pre-crack damage and the crack growth rate; inspection procedures, therefore, depend upon such varied factors.

With regard to fatigue-damage detection by means of NDI methods, the situation is somewhat similar to that of fatigue data. There is a large amount of published information scattered throughout nondestructive-testing and fatigue literature. In fact, one could speak of an information "explosion" in this area. On the other hand, this information has not been compiled and assessed; hence, full utilization of the existing knowledge is difficult. Moreover, there appears to be a lack of description of applications of NDI methods to fatigue damage detection under field and service conditions and on the problems encountered in these applications. Thus, the experience gained and the knowledge developed in a specific application is often not being transferred to a similar application. Consequently, a high-effort survey and assessment of the available information on NDI methods as applied specifically to fatigue-damage detection appears to be a real need.

Presently available NDI methods for field and service use permit detection of fatigue cracks of various sizes. Further development will lead to improvement in resolution (that is, in ability to detect even smaller cracks) but it is doubtful that these methods will be able to detect damage prior to crack initiation. Consequently, the development of new methods that can detect, in field use, very early damage is highly desirable. Although several methods have been noted as under current study, none of these now show clear promise for the immediate future.

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13. ABSTRACT

Following a brief section on the basic mechanisms of fatigue, destructive tests for measuring fatigue effects are described. Current fatigue problems are discussed, including poor quality cont ol of materials, effects of fatigue on behavior of residual stresses due to mechanical working, and of various heat treatments. Research underway on long lifetime fatigue, low-cycle fatigue, and crack propagation is described. A discussion of methods for predicting and preventing fatigue damage leads into an extensive discussion of nondestructive test methods for determining fatigue damage. The many gaps in information on fatigue and the needs for future research are pointed out.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Damage						
Eddy Current Testing						
Fatigue (Materials)						
Fatigue Failure						
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